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Power electronics evolution in wind turbines—A market-based analysis

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ABSTRACT

The aim of the paper is to analyse the evolution of wind turbine concepts or topologies with a specific focus on their power electronics content, and to demonstrate the tendency of wind turbine manufacturers towards the development of generators connected to the grid by means of power electronics converters. The paper provides a review of the power electronics converters used in wind turbines and a briefer description of the components that make up those converters. Then the research, supported by a market study based on 91% of the total installed wind capacity during the period 2000–2009, demonstrates the evolution of the wind turbine market towards the use of power electronics converters with their market share increasing from 38% in 2000 to 80% in 2009. In particular, the type D wind turbine configuration – containing a full power converter – appears set up to increase market share in the next five years. If projections of these findings are realised wind turbines without a power converter could be reduced to a niche market as soon as 2013. The paper refers these findings to, among other reasons, the increasingly more strict technical requirements of the grid operation codes. Finally, the paper details some of the current research and development trends plus a vision of the future by the industry.

Contents

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1. Introduction

Wind power represented 9.1% of the total installed capacity in the 27 Member States of the European Union (EU-27) by the end of 2009 [1], and at 132 TWh the share of wind electricity production is estimated at 4.5% of the total net electricity generation in 2009.[1] Nowadays wind electricity contributes more than 10% of the net electricity supply in four EU-27 Member States.[2] The European Union (EU) energy policy of having a 20% renewable energy contribution by 2020, which would involve a 33% renewable electricity share [2], and its supporting elements [3,4], involves that this share will increase significantly until 2020. In addition, security of supply and climate change policies suggest that the tendency will continue beyond 2020.

This high penetration level of wind electricity impacts to a certain extent the operation of the power system due to the stochastic character of the wind resource. To reduce the extent of these impacts the transmission system operators (TSOs) in each country have developed requirements to connect wind power generation to the public electricity system – grid codes. Compliance with these technical requirements was achieved by evolving in a clear direction: the use of power electronics converters [5–7].

Based on the four wind turbine concepts, configurations or topologies described by Hansen and Hansen [8] and BTM [9] among others, the objective of this paper is to analyse the evolution of wind turbine concepts with a focus on the complexity of the power electronics devices that they incorporate. This analysis is supported by a detailed market study of the installed wind turbines in the period 2000–2009, where the turbines are classified following those four topologies. In order to set up the scene in a clear way, the scope of the article includes an updated compilation of power electronics converters used in wind turbines.

The paper is organised as follows: Section 2 describes the role of power electronics in the wind power context: grid code compliance and turbine control systems; Section 3 reviews the power converter technologies and the wind turbines topologies; Section 4 describes and analyses the market study of the wind turbines installed between 2000 and 2009, and Section 5 presents the research and development trends.

2. Power electronics in the wind power context

Wind turbines (WT) as we know them today are around a quarter-of-a-century-old generation technology. They deal with a variable source of energy which, by this nature, can affect the quality of the power generated. During its infancy the technology was not subject to specific demanding technical requirements – but this has changed: nowadays, wind turbines are regarded by TSOs like any other generation technology and face therefore increasing quality demands. WT technology has evolved accordingly and uses power electronics (PE) components to output an electrical signal that complies with those power quality demands. While achieving this goal is the main role of PE devices used in wind turbines, it is not the only one. The other important role of PE is as part of the control system of the wind turbine e.g. in order to achieve the maximum power output. Fig. 1 shows an example of a WT configuration that has a PE component called full power converter (FC), which settles between the generator and the transformer.

[1] Figures calculated from Eurostat and Member State sources and include assumptions on average European load factors and projection to 2009 of Eurostat-published data.

[2] Sources include Eurostat and the different national transmission system operators and/or national energy agencies of ES, IE, PT, DK.

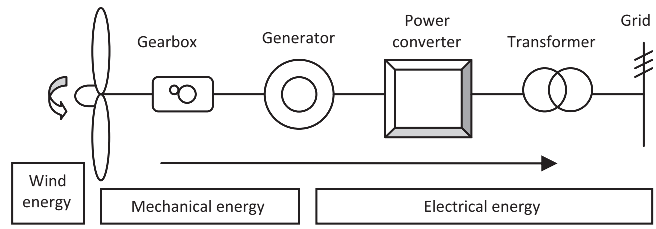


Fig. 1. Conversion of wind energy into electrical energy in a wind turbine with full power converter.

2.1. Wind turbine grid integration requirements: grid codes

Specific grid codes define the requirements to connect wind power generators to the grid. These mainly include active power control, frequency control, voltage and reactive power control and fault ride – through capabilities[3] [10]. However, not all grid codes have the same demands on wind power as they differ significantly between countries. For example in the important issue of standing grid frequency deviation the British grid code requires unrestricted continuous operation in a band from 47.5 to 52 Hz whereas this band in the Swedish code is from 49 to 51 Hz and it further depends on the wind farm installed capacity [11]. It has been suggested that common, Europe-wide grid code requirements would reduce barriers to wind turbine technology (and costs) as currently manufacturers have to adjust the turbines for each country network. The opposite reasoning suggests that applying high-level requirements in countries with low wind penetration would involve unnecessary costs [12].

Table 1 summarises how the different WT configurations traditionally used [8] fulfil grid requirements. Of the four wind turbine configurations types A and B are not connected to the grid through PE while types C (also called here doubly fed induction generators (DFIG)) and D (also referred to as FC) are respectively partially and fully connected to the grid via a PE converter device. WT configurations will be explained in detail in Section 3.

It has to be noted that a type D WT configuration is the one which best complies with any current grid code requirements.

2.2. Power electronics in WT internal control system

Power electronics devices also form part of the control system of a wind turbine and as such they serve a dual purpose: maximising power output for any given level of available wind power by managing the aerodynamic system, and controlling the output or stop generation altogether when the grid suffers instabilities or the wind is too strong and could damage the turbine [6].

The aerodynamic design of wind turbine blades is fundamental to reach a high wind power capture and to convert it into rotating mechanical power. Mechanical power is most commonly transmitted thought a gearbox from the turbine rotor-connected, low-speed shaft to a generator-connected, high-speed shaft. The high-speed shaft is linked to the rotor of the generator where the mechanical power is converted into electrical power (see Fig. 1).

Fig. 2 shows the control system of a type-D wind turbine along with monitoring data (dash lines) and control instruction lines (thick lines). Two main control subsystems can be identified: wind turbine control and converter control. The former includes power control, grid synchronisation and monitoring techniques, wind turbine logic and safety modules [14]. The converter control is split

[3] Tsili et al. [12] give a detailed review of grid code technical requirements in USA, Ireland, AESO and Hydro-Quebec (Canada), Germany, Denmark, UK, Nordel, Belgium, Sweden, New Zealand, Italy and Spain.

Table 1
Wind turbine configurations and how power electronics are used to fulfil grid codes [7,13].

		Types A and B	Type C (DFIG)	Type D (FC)
Active power control	WT concept can provide it?	Limited	Yes	Yes
	How? Compensation	Pitch or stall control (type B also via rotor speed control)	Pitch or stall control, variable-speed generator and power converter	
Frequency control	Can provide it?	No	Yes	Yes
	Compensation by	None. WT is directly connected to the grid	Partial power converter	Full power converter
Reactive power control	Can provide it?	No	Yes	Yes
	Compensation by	Extra devices (capacitor banks or static compensation devices, like SVCs or STATCOMs)	Variable speed generator and (partial/full) power converter	
Reactive power during VRT	Can provide it?	No	Not always	Yes
	Compensation by	Extra devices (capacitor banks or static compensation devices, like SVCs or STATCOMs)	Extra device needed (a crowbar)	Full power converter

in two sides, generator-side and grid-side, and receives input data from the wind turbine control and other data measured throughout the turbine. Controlling the generator-side converter implies adjusting the rotor speed of the generator to obtain maximum power output following a maximum power point tracking (MPPT) algorithm linked to the wind speed [5,6,15]. The MPPT can be achieved following different control methods all of which aim to optimise the tip speed ratio [16]. The grid-side converter control is responsible for the quality of the electrical signal, and thus for the compliance with grid code requirements [6]. It generates a pulse-width modulation (PWM) voltage whose fundamental component includes the grid frequency [17].

3. Technology

Power converters are PE devices composed of semiconductor elements that modify an electrical signal from one kind or level to another. Depending on the relation between the type of current input and output power converters are classified in [18]:

- rectifier (input AC/output DC)
- inverter (input DC/output AC)
- chopper (input DC/output DC)
- frequency converter (input AC/output AC), also called, cycloconverter or phase converter

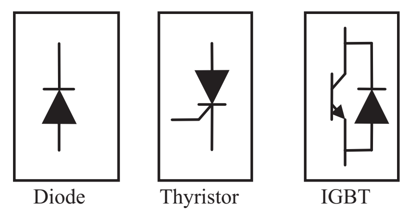


Fig. 3. Semiconductors used in power converters and their symbols.

A power converter can also be made of the union of two or more basic converters, e.g. power converters in wind turbines normally consist of a rectifier (generator-side converter) and an inverter (grid-side converter).

3.1. Semiconductor devices in power electronics

Attending to their degree of controllability the semiconductors used in power converters can be classified into three groups (Fig. 3) [18,19]:

1. Diodes – elements that allow current pass only in one direction. They are not controllable.
2. Thyristors or semi-controllable switches – are grid-commutated components latched 'on' by a control signal but must be turned

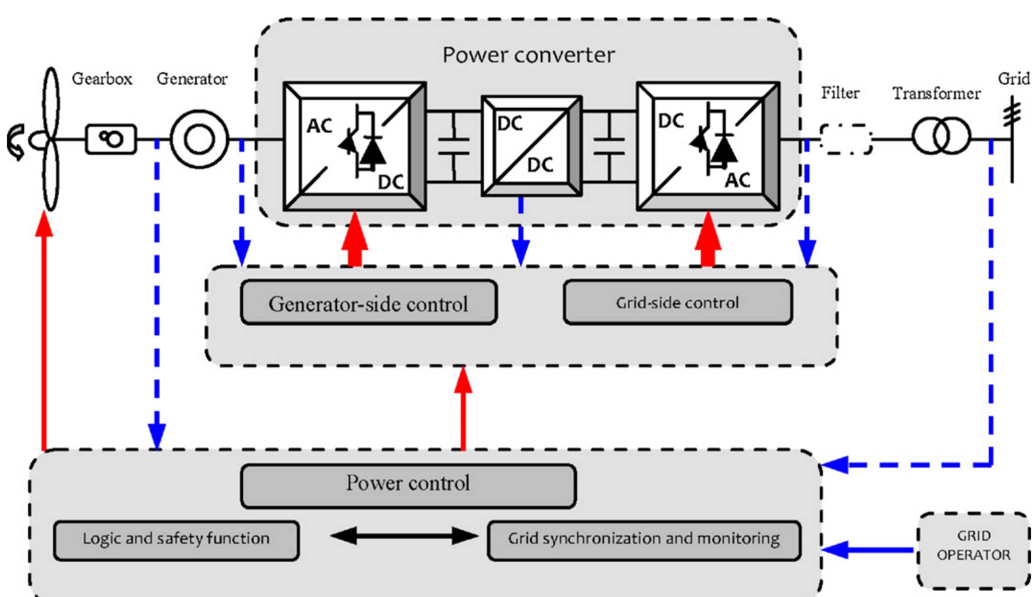


Fig. 2. Levels of control in a wind turbine with full-scale, back-to-back power converter with a DC/DC stage [14].

'off' by the power circuit. A thyristor consumes inductive reactive power and it is not able to control the reactive power. The most relevant thyristors are the gate turn off (GTO) and the integrated gate-commutated thyristors (IGCT).

3. Controllable switches, also called self-commuted converter systems, are turned 'on' and 'off' by control signals, and are bidirectional. Controllable switches are able to transfer active power and reactive power in both directions (AC/DC or DC/AC). They include bipolar junction transistor (BJT), metal oxide semiconductor field effect transistor (MOSFET) and insulated-gate bipolar transistor (IGBT) [5].

Controllable and semi-controllable switches can be classified as well into current-source devices like BJT, or voltage-source devices like MOSFET, GTO and IGBT. Current-source devices and voltage-source devices are respectively used in current-source converters (CSC) and in voltage-source converters (VSC).

VSC technology offers faster control over a wider range of voltages and its size is smaller than thyristor controlled ones. On the other hand, VSC technology is composed of self-commutated semiconductor switches which are more expensive, have higher losses and smaller voltage ratings when compared to thyristors [20].

3.2. Components of power electronics devices

The main components of power converters for wind generators are the following (Fig. 4):

- The semiconductor elements which make up the rectifier and the inverter. IGBT's are the semiconductors most commonly used in power converters [5].
- A DC-link capacitor or DC bus. It is located between the rectifier and the inverter. The DC-link capacitor voltage has to be maintained stable in order to achieve a decoupling (see Section 3.3.1.1) between the generator-side converter and the grid-side converter and thus to allow the control of both sides independently [5,6,15].
- Output filter to filter out the main harmonics. This filter normally consists on inductances and capacitors connected between the grid-side converter and the grid [21].
- The control system composed by electronic chips and microprocessors. Sensors measure the different variables needed for its correct functioning, these data are then analysed by the microprocessor which is able to send output control data (see Fig. 2).

Power converters need ancillary systems such as a cooling system and a (dynamic) braking system. The latter provides protection from rotor over-speed under abnormal conditions [22] whereas the former is necessary to dissipate the heat generated by the PE devices. This can be water- or air-cooled.

3.3. Classification of wind turbine power converters

Because they offer full controllability of the generated power, the main power converter topologies currently used in wind turbine systems are the bidirectional power converter and the unidirectional power converter.

3.3.1. Classification according to the direction of conversion

It is the semiconductor elements used in a power converter that define the direction of the conversion, and thus converters can be unidirectional (from source to load) or bidirectional

3.3.1.1. Bidirectional power converter. The bidirectional power converter, also called back-to-back converter, is the state-of-art [6]. It consists of controllable switches (usually IGBT) on both sides of the power converter (rectifier and inverter) and a DC link. The converter in Fig. 2 is a back-to-back converter.

Since the generator-side converter is decoupled from the grid-side converter by the DC link, the generator is able to operate at a wide variable frequency range to achieve optimal power output. The power generated is then transferred to the grid through the grid-side converter which controls active and reactive power independently and improves the dynamic response [5]. Active and reactive control is implemented controlling the DC-link by keeping it constant; for every WT shaft speed, an optimum value of DC voltage and current can be identified. Every optimum DC value defines the reactive power that attains maximum active power output [15].

This topology of power converter can be used in both synchronous and asynchronous wind generators. In the case of permanent-magnet synchronous generators (PMSG, a generator used in type D WT configurations) a boost DC/DC converter can be included as part of the DC link, incorporating the following advantages: more flexible control of the inverter as it does not have to control the DC-voltage (the control of the generator-side DC voltage will be done through the variation of the switching ratio, while the DC voltage of the inverter-side is maintained according to the DC reference voltage, see Fig. 2), and less losses because a DC/DC converter allows using techniques for selective harmonic elimination [15]. On the negative side there are some losses because the power converter has an extra level of conversion. Despite this, overall losses are reduced.

3.3.1.2. Unidirectional power converter. The unidirectional power converter consists of a diode-bridge rectifier on the generator-side converter, a thyristor or a controllable switch in the grid-side converter, and a DC link (Fig. 5). The disadvantage of using thyristors is that they create reactive power demand and harmonic distortion that needs to be compensated with additional components [15].

It is possible to achieve the maximum power output by controlling the DC-link voltage [15]. Because of the diode-bridge rectifier used, the variable-speed operation of the wind turbine is achieved using an extra excitation system in the generator [6]. Using controllable switches in the grid-side converter allows a decoupled control of the active and reactive power delivered to the grid.

This topology of power converter is mainly used in wind turbines with synchronous generators [6,15]. As in the case of back-to-back converters a boost DC/DC converter stage can be included as part of the DC link when the generator uses permanent-magnet synchronous generators (PMSG).

3.3.2. Classification according to their architecture

According to their architecture power converters can be modular, multilevel and matrix.

Modular converters are composed of a number of power converters connected in parallel. Because the number of modules used depends on the produced power (the higher the wind speed the most switches used), their main advantage is that they are more efficient at low and medium wind speeds [6] (Fig. 6).

Multilevel converters create a sinusoidal voltage from several levels of DC voltages, which normally are obtained from capacitor voltage sources although batteries are used as well. They are preferred for larger wind turbines, above 1 MW [23]. Multilevel converters offer different topologies using diode-bridges, bidirectional switches, cascade H-bridges, etc. [24]. The advantages of the latest multilevel (three-level) converters are a better voltage waveform, the reduction of harmonics content compared to the standard two levels converters, the increase of the power rating and the decrease of the voltage stress across the switches [23], which decreases the switching losses per switch. However, because of the high number of semiconductors the conduction losses may be higher. Another disadvantage lies in the voltage imbalance between

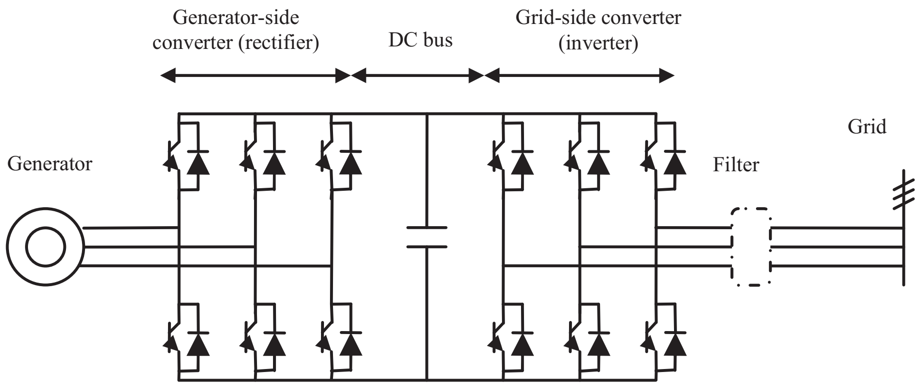


Fig. 4. Power converter configuration in a FC wind turbine showing the DC bus, IGBTs, and the harmonics filter.

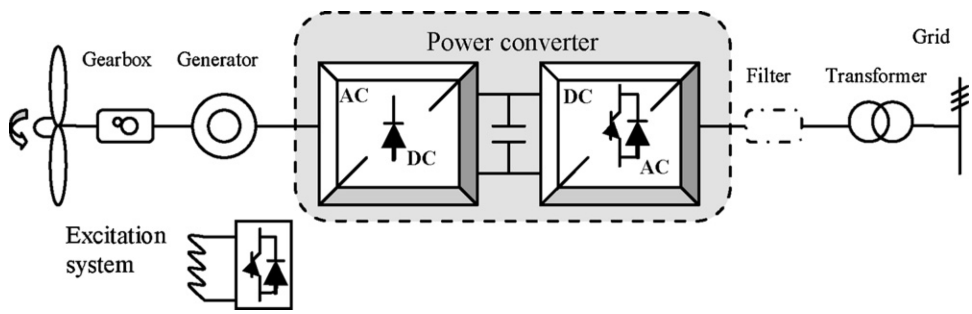


Fig. 5. Unidirectional power converter for a full converter wind turbine.

the upper and the lower DC-link capacitors, but this can be solved by controlling the modulation of the switches via hardware [6].

A special bidirectional power converter topology is the matrix converter, a direct AC/AC converter of the variable AC from the generator into the AC signal as the grid requires, in one stage, without using any intermediate DC link [25]. Matrix converters are technically complex [5] as they consist of nine bidirectional switches, 18 switches in total, set in a layout such that any input phase may be connected to any output phase at any time (Fig. 7). Every individual switch can operate as rectifier and inverter.

Matrix converters have the advantages of obviating the conversion losses incurred in a DC link, and that their control is performed in one single converter. On the negative side the absence of a DC link introduces two main disadvantages [57]: first, the grid side of the converter is directly affected by the distorted and/or unbalanced input voltage from the generator side, which may also cause harmonics in the output [26]; and second the need of a complex modulation strategy. Another disadvantage is that the high amounts of switches increase the cost of the converter [15]. Although these converters do not have industrial applications yet, several studies suggest that matrix converters could be applied in wind turbines [27–29].

In both multilevel and matrix converter the transformer may be omitted [30].

3.3.3. Flexible AC transmission systems (FACTS)

This is another power electronics technology family that can be used in wind farms to regulate reactive power and in particular to provide the reactive power needed during and after a grid voltage fault [31]. Two generation of FACTS devices can be distinguished: an older one based on thyristors and newer one based on VSC [20].

The two types of FACTS used in wind farms are the static VAR (volt-ampere reactive) compensator (SVC) composed of capacitors and inductances controlled by thyristors, and the static compensator (STATCOM) based on VSC. The advantages of STATCOM over SVC are the capability of maintaining the reactive power output at its nominal value over a wide range of voltages, while a SVC only has limited capability when voltage is reduced. In addition, STATCOMs have faster control response [20].

FACTS devices can be installed inside each wind turbine or externally, covering the needs of a whole wind farm [31]. A type of SVC, the thyristor-controlled resistor (TCR), is the most appropriate for a single wind turbine, whereas STATCOM is the most suitable for a wind farm. The advantage of using a wind-farm FACTS is that it

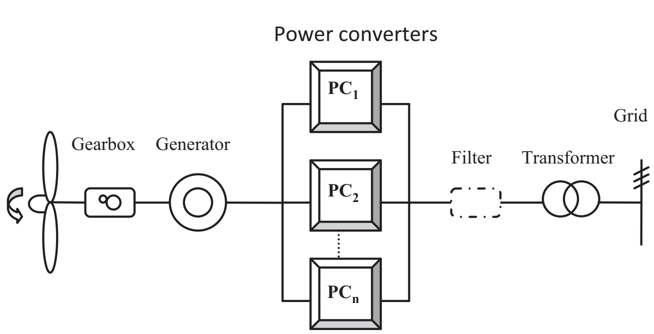


Fig. 6. Modular power converter for a full converter wind turbine.

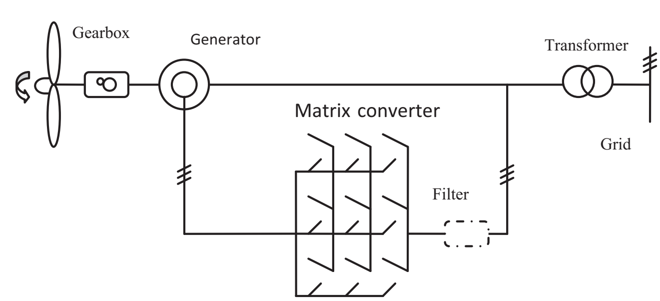


Fig. 7. Matrix converter in a DFIG wind turbine.

creates a firewall isolating the wind turbines from grid disturbances. There is a disadvantage though: if a fault occurs inside the wind farm the device cannot correct it and the wind turbines might be affected.

One of the most advanced FACTS devices, the Unified Power Flow controller (UPFC), consists of two power converters: one treated as STATCOM and the other as a static synchronous series compensator (SSC, a FACTS-SVC based device which controls the power flow and the damping of power oscillations), linked by a DC-link. UPFC has only very few wind-related experimental applications due to its high cost [20].

4. Wind turbine classification according to their power converter

Generally wind turbine configurations are classified in four main types. Type A configuration has a fixed-speed rotor while the other WT configurations operate at variable speed. Variable speed WTs vary the speed of the rotor if the wind speed and torque vary, therefore achieving better efficiency at low wind speeds, a reduction of stress supported by the tower, gearbox and drive train, and the control of power injected to the grid [5,6,32].

Both kinds of machines have to control power generation and to limit rotor speed when wind speeds are high and dangerous for the generator. This control can be done by stall control (fixed blade position whose aerodynamic design forces a stall of the wind to build up along the blade at high wind speed), active stall (blade angle is adjusted thus creating stall along the blades at dangerous wind speeds) or pitch control (blades pitch and are driven out of the wind at higher wind speed) [33].

The power electronics aspects defining these configurations include WT that have no PE power converter (types A and B), partially rated power converter (type C) or full-scale power converter (type D).

4.1. Wind turbines without power converter

WTs without power converter include types A and B of the general WT classification. In a type-A WT (Fig. 8) electricity is produced in a squirrel cage induction generator (SCIG) which is directly connected to the grid and operates almost at fixed speed, a maximum torque variation of 1–2%. The power can be aerodynamically limited either by stall or active stall [7]. The connection of induction generators to the grid produces transients (short-time currents with high inrush rating), which cause disturbances in the grid and could cause high torque damages in the WT drive train. In order to avoid transients a type-A WT requires a power electronics device called soft starter which achieves torque reduction and a smooth connection of the generator to the grid by adjusting the firing angle of its thyristors during a predefined number of gird periods, [5]. Induction generators consume reactive power which needs to be compensated usually through a capacitor bank, although FACTS devices can also be used.

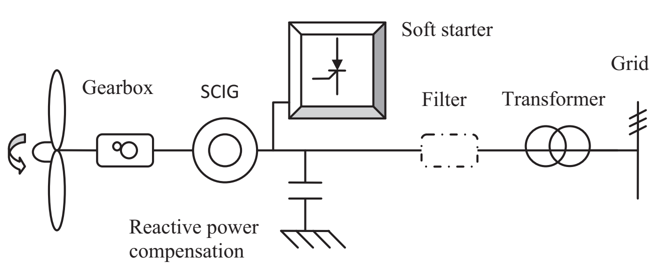


Fig. 8. Scheme of a type A wind turbine.

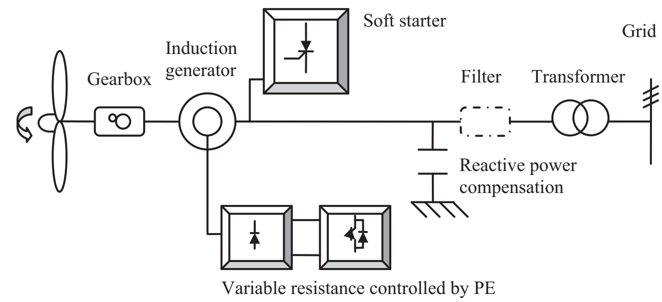


Fig. 9. Type B wind turbine with variable resistance controlled by PE, and no power converter.

The advantages of type-A WTs are low cost and high reliability. However, their reactive power control does not have a fast response [7]: because they only operate at constant speed they require strong grids for stable operation and robust, expensive mechanical construction in order to absorb high mechanical stress [5].

Type-B WTs allow variable speed operation of the wind turbine rotor by including dynamic-slip induction generators where the induction generator is a wound rotor with a variable rotor resistance controlled by PE (Fig. 9). By changing the resistance in the rotor windings of the generator, the generator slip varies and achieves speed ranges in the generator of 2–5%. This solution also needs a soft starter and reactive power compensation [5,7].

Type-B WTs are connected to the grid through brushes and slip rings, which is a more complex solution and constitutes a drawback when compared with the simple technical design of type-A generators. It also raises the maintenance requirements [5].

4.2. Wind turbines with partial power converter

Type-C WTs are characterised by the use doubly fed induction generators (DFIG) where the stator, the fix part of the generator, is directly connected to the grid while the electrical connection of the generator rotor is through slip rings and a partial power electronics converter (Fig. 10). The generator delivers energy always at grid frequency whether the turbine rotor is turning at either supersynchronous or sub-synchronous speed. The slip varies with the power flowing through the power converter, which only transfers about 30% of the total power, and this is enough for a rotor speed variation in the range of ±30% of the nominal speed. By controlling the active power of the converter it is possible to vary the speed of the generator rotor, which then better adapts to the speed of the turbine rotor [6]. A type-C turbine typically uses a back-to-back, IGTB-based switching converter (see Section 3.3.1.1).

During grid faults type-C WTs may not be able to provide sufficient reactive power. To protect the WTs during these faults an active crowbar can be used (Fig. 10) [13]. The crowbar short-circuits the rotor windings of the DFIG and prevents the generator-side converter from switching, protecting it against any over-current or over-voltage [34]. When the crowbar is activated and because the

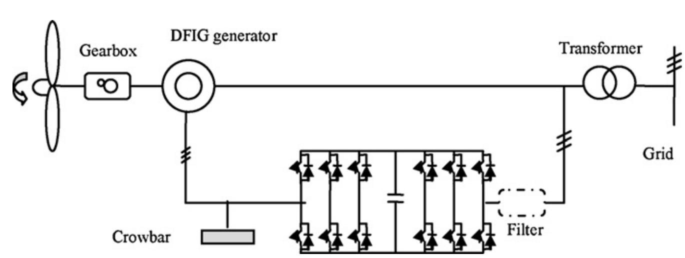


Fig. 10. Type C wind turbine: DFIG with crowbar and a detailed power converter scheme.

generator-side converter stops working, the control of the active and reactive power is no longer independent. The generator then behaves similarly to an ordinary induction generator. The active power output is controlled by the blade pitch angle to prevent over-speeding. The reactive power required during this fault is regulated by the grid-side converter; in case of weak grids the reactive power requirements can be provided by an external dynamic reactive compensation device [34], such as a STATCOM. When the fault has been cleared and the voltage and the frequency values have been re-established, the crowbar is deactivated thus restarting the generator-side converter circuit. The compensation during grid faults can also be arranged by an energy storage system [34].

4.3. WTs with full power converter

The WT configuration which corresponds to a full-scale power converter is type D (see Fig. 2). These are variable-speed wind generators where a power converter is located between the generator and the transformer/grid. Also in this case the power converter mainly used is the back-to-back, IGTB-based converter.

Because the generator is decoupled from the grid it is not obliged to operate at a fix frequency. In addition both active and reactive power can be fully controlled independently [5], which could be exploited further (see Section 5.3). Achieving this decoupling results in a good control of the dynamics of the wind turbine and generator during grid disturbances [6]. It also has fast control of power output – same as type-C WT. However, the disadvantage of type D is that it is a more complex system with more sensitive electronic parts [5].

Generators in this topology can be asynchronous, e.g. Siemens' NetConverter® solution [35], or synchronous, whether electromagnet or permanent-magnet (PMSG) [5]. They can be connected to the wind turbine rotor directly or through a gearbox, therefore they can be low-, medium- or high-speed, around 20, 600 or 1500 rpm, respectively. Examples include Enercon E82 [36], Gamesa G128/4.5 [37], and REpower 5 M [38], respectively.

5. Market evolution

The market for power electronics in wind turbines is analysed here in connection with the evolution and market share of the different wind turbine concepts.

5.1. Methodology

The reference paper in the study of wind turbine concepts [39] proposes a methodology based on the collection of data for all WT installed in the world, the distinction of WT models by their configuration (A, B, C, D as described above), and the mapping of the installations according to these configurations. In this paper we have followed this methodology in the essential, as described below.

The basic database was obtained initially from the global Power e-Track database of wind turbines, wind farms or phases of wind farms [40], which contained 8176 records where the WT model, WT manufacturer and year of installation (2000–2009) were identified, for a total of 90 GW. This is 61.7% of the global installed capacity during the period according to GWEC [41].

In this dataset Chinese data were a particular concern because of the limited information included: only wind turbine configurations for 7 GW were identified whereas as much as 25.56 GW were installed during the period. The Chinese Wind Energy Association [42] kindly provided a split of Chinese WT installations according to their configurations and these data were used.

Subsequent refining of database entries took place by individually searching in the Internet ([43–45] and other databases) with the aim of identifying at least the turbine model or the maker, the wind farm capacity, and the year of operation, until the identified WT configuration reached 82% of the installed capacity (120 GW). The main gap at this stage was the Spanish and German installations. Spanish Ministry of Industry, Tourism and Commerce very kindly provided a dataset including the year of operation, which was compared with AEE [43] and a GlobalData update ([40], 7th/10/2010) to reach 90% of installed capacity. Further refining was based on developers' public databases and some manufacturers' references (e.g. REpower 2010). Lastly, BTM [46] annual installed capacity was used for specific updating (e.g. Enercon's[4] 2009 data).

Through this refining process the database eventually contained 400 turbine models and the turbine configuration was identified for 91% of all installed capacity in the period 2000–2009, a total of 133 GW.

5.2. Analysis

The results of the processing of these data are presented in Table 3 where GWEC annual installed capacity figures are also included. The table shows that the captured share of world turbine installations is in most years above 90%, which gives a high reliability to the dataset used for this research. Fig. 11 shows the trend of the absolute figures in gigawatts installed per year.

Fig. 12 shows the evolution of the split of wind turbine concepts in percentages. The trend towards wind turbines with power electronics converter, either partial (type C, DFIG) or full (type D, FC) is increasing dramatically in the decade under study, this is a result consistent with the increasing demands of grid codes. In effect, whereas at the beginning of the decade less than 38% of installed wind turbines had partial or full converter, as early as 2002 this figure increased to 45% and then to 80% by 2009, effectively doubling its market share in one decade.

The trend shown by the actual installation is towards the disappearing of types A and B or at least towards their reduction to niche markets with low or no grid code requirements, or where they can connect through a wind farm-level FACTS. In effect, the projections resulting from the figures since 2005 show this dramatic evolution (see Fig. 13) and suggest that by 2013 there could be no new type A or B turbines installed in the world.

By contrast, an analysis by absolute numbers shows that the capacity of non-power-converter turbines being installed keeps increasing even if these configurations cannot keep pace with the high increase (28% annual average, 810% in total in the decade) of overall installations. As Fig. 11 and Table 2 show, the sum of type A plus type B capacity installed actually increased a 180% during the period, from 2000 to 5500 MW per year.

[5]Since 2006 no significant introduction of new type A machines occurred other than in India and China; there the Suzlon S52-600; Southern Wind Farms GWL225; Goldwind GWS48/50-750 and Windey WD49/50-750 (the last two with REpower technology) had significant sales. In Western countries only the Vestas V82-1.65 (with ActiveStall technology and associated FACTS) has been installed in significant numbers (North America, UK). By contrast in the same period several full-converter machines were introduced and had a significant deployment:

[4] The BTM database of capacity installed per manufacturer and year gave the opportunity to complement our detailed database of installations only when (a) the manufacturer only makes WT of one single configuration during a given year, (b) there was a significant gap in our database for that manufacturer and year, and (c) it was sure that those WTs were not installed in China. This was the case for Enercon (FC machines) in 2009.

[5] Several manufacturers and models are quoted here. All the model information was obtained by searching in the Internet the web sites of the manufacturers.

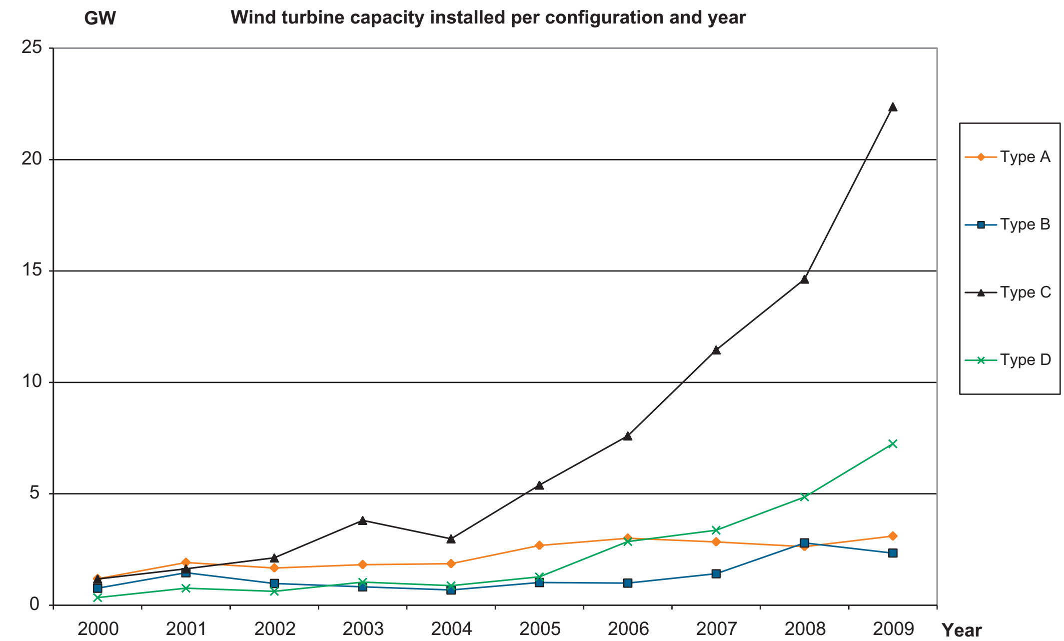


Fig. 11. Evolution of installed capacity per turbine concept, 2000–2009, in absolute numbers.

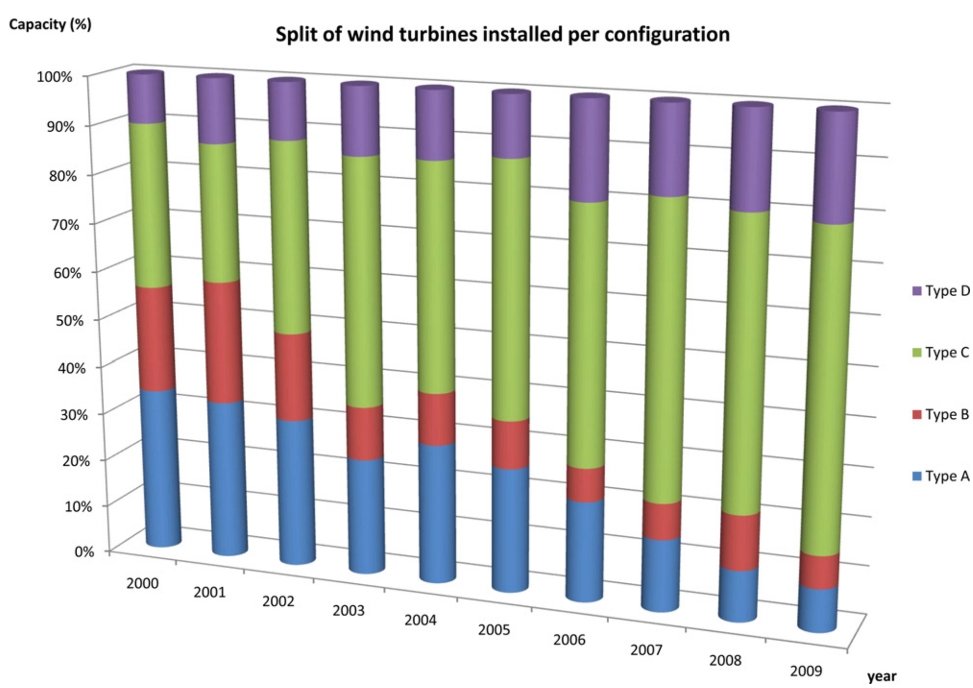


Fig. 12. Split of wind turbine installations according to their configuration, 2000–2009.

Table 2
Installed capacity in the study (MW/year-configuration) and comparison with total installed capacity.

MW installed\Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Type A	1,192	1,924	1,677	1,825	1,866	2,686	3,015	2,849	2,638	3,109
Type B	764	1,465	980	830	687	1,023	997	1,414	2,802	2,346
Type C	1,179	1,639	2,126	3,812	2,984	5,394	7,602	11,462	14,636	22,369
Type D	346	764	629	1,039	878	1,282	2,858	3,370	4,861	7,250
Total	3,481	5,792	5,412	7,505	6,416	10,385	14,471	19,094	24,936	35,074
GWEC total [41]	3,760	6,500	7,270	8,133	8,207	11,531	15,245	19,865	27,051	38,343
Percentage	93	89	74	92	78	90	95	96	92	91

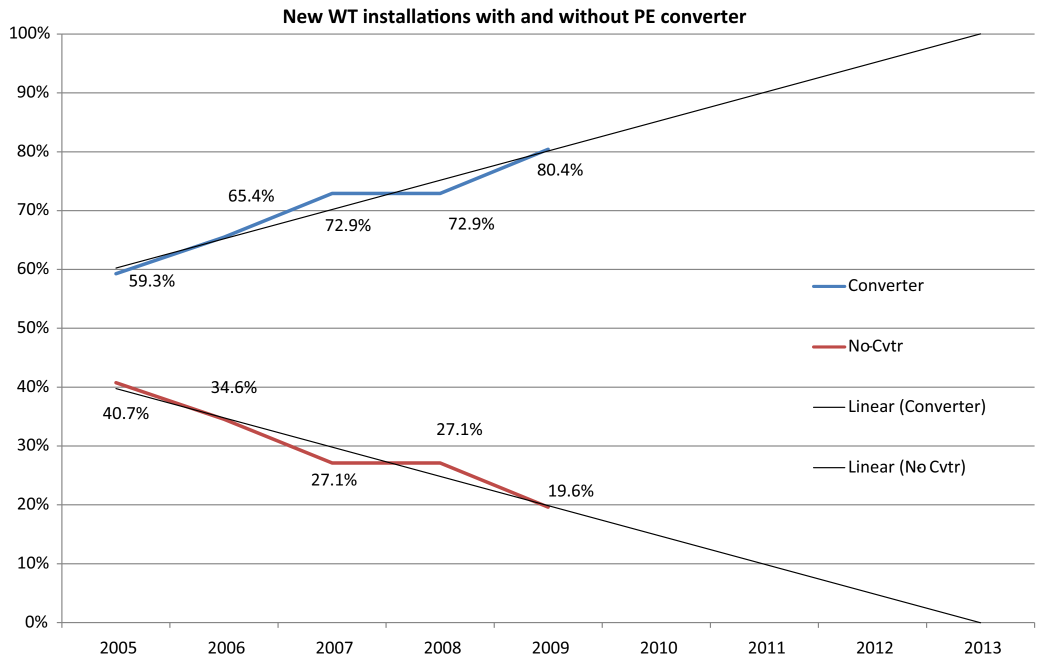


Fig. 13. Trends in wind turbine installation from a power converter view, 2005 onwards.

Table 3
Evolution of the wind turbine market, in percentage, according to WT configuration.

Configuration	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Type A (%)	34.3	33.2	31.0	24.3	29.1	25.9	20.8	14.9	10.6	8.9
Type B (%)	21.9	25.3	18.1	11.1	10.7	9.8	6.9	7.4	11.2	6.7
Type C (%)	33.9	28.3	39.3	50.8	46.5	51.9	52.5	60.0	58.7	63.8
Type D (%)	9.9	13.2	11.6	13.8	13.7	12.3	19.7	17.6	19.5	20.7

DW54-900 (EWT); E-53, E-70-2.3, E-82-2.3, E-82-3.0 E-126 (Enercon); GW70, 77 and 82 (Goldwind with VENSYS technology); J82 (Japan Steel Works); IWP-V77 (Industrias Metalurgicas Pescarmona, VENSYS licensee); several Liberty models (Clipper); M5000 (Areva-Multibrid); SWT-2.3-82VS, 2.3-93, 3.6-107 (Siemens); VENSYS 78 (VENSYS); WWD-3 (WinWinD); Z72/82 (XEMC-Darwind).

5.3. Trends: full converters related to the drive train

Full converters (FC) are necessary when the wind drive configuration is direct-drive (DD), i.e. a direct connection of the wind turbine rotor to the generator rotor without a gearbox. The generator is then no longer required to run at high speed to provide grid frequency output. In those cases the frequency, and sometimes even voltage, of the generator is not assured constant – or is not convenient that it is assured constant, and the FC ensures the right quality output to the grid.

The state-of-the-art in power electronics use in wind turbines is very varied mainly because of two reasons: the increasing demands of grid codes and the reduction of power electronics cost. These conditions have also led to more varied configurations. Nowadays many machines use a FC in conjunction with a geared drive e.g. for reducing overall nacelle mass[6] while taking advantage of the reduced maintenance needs of 1- or 2-stage gearbox machines.[7] Examples of the latter approach include the Multibrid and Siemens turbines quoted above among others, whereas pure FC-DD manufacturers include Vensys and Enercon.

5.4. The evolution of DFIG (type C)

The doubly fed induction generator configuration has proven most successful both in absolute and relative terms in the period under study. DFIG wind turbines covered 64% of the market in 2009, up from 34% in 2000. In absolute terms, DFIG installed capacity increased from 1180 MW in 2000 to 22370 MW in 2009, nearly a 20-fold.

DFIG is the leading configuration partly because of the support of investors: it is cheaper than FC and a proven technology for onshore wind farms [48].[8] In the *S*-curve modelling the diffusion of technological innovations, DFIG turbines would currently be in a position encompassing both the early and the late majority stages [49], and it would have been in that position for the later years of the period under study. However, there seems to be signs that this technology has reached its summit and full converter machines may take over the role of most popular configuration in the medium term.

[6] BNEF [47]: the mass of the generator in a FC, 5-MW gearless machine is of the order of 132 t vs. the 17 t of the generator in a 5-MW DFIG wind turbine. In the first case the gearbox mass avoided is 63 t and thus the net increase resulting from a DD-FC configuration is 52 t heavier than a DFIG configuration.

[7] Industry claims that the weakest of the gearbox stages is the third one which is the one increasing the gear ratio up to 1:100.

[8] At the recent wind energy fair Husum 2010 the authors had the occasion to interview several wind turbine and component manufacturers including Converteam and Aerodyn, and this view was widely supported. Note that much of what follows is the result of those interviews.

Table 4
Possible future evolution of some wind turbine functions in a more systemic view.

Function	Today's state-of-the-art	The mid-term future
Energy transmission to the generator	Either a main shaft with a 3-stage gearbox conveying the rotating movement to a high-speed (1500 rpm) wound-rotor generator; or direct-drive transmission to a low-speed, permanent-magnet (PM) generator, with hybrid intermediate designs. Generators are low-voltage (below 1000 V) and largely high speed	Direct-drive connection to a MV, PM or high-temperature superconductor (HTS) generator. Legacy designs will co-exist as well as advanced hybrids with 1/2-stage gearboxes and MV generators. Low-speed generators, maybe DC generators
Energy conversion from mechanical to electrical		
Energy adaptation to grid codes	Doubly fed induction generators (DFIG) allowing a limited control of the sinusoidal voltage quality. Turbine-based full converters (FC) transform the alternate current (AC) from the generator into direct current (DC) and then back to the required AC signal. Transformers to up to ~33 kV built-in the nacelle or at the foot of the tower. Substations connecting to the distribution (approx. 33–132 kV) or transmission (above 132 kV) networks	Medium-voltage link, either AC (with floating frequency) or DC, from the turbines to the substations. There, shared inverters and transformers will adapt to the grid requirements. If necessary, harmonics filters and other adaptors will be placed at the substations

In effect, with the increase in offshore installations, with grid codes becoming more and more demanding (doubly fed converters need to be increasingly complex in order to be compliant with these new grid codes), and the attractiveness of not having gearbox issues, the industry believes that a solution involving a full power converter (with a PMG) becomes now economical in some countries [50]. Offshore wind farms, where reliability demands are even stronger than onshore due to the difficulty to access the turbine for maintenance, the tendency is to go for solutions without a gearbox – or with gearboxes with fewer stages, and therefore lower-speed generators are necessary. This scenario is a perfect match for a full power converter.

6. Research and vision

European research in wind energy is supported by a technology platform, TPWind, the European Energy Research Area (EERA) and the Wind European Industrial Initiative (EII) under the umbrella of the Strategic Energy Technology Plan of the European Commission [4]. In practice this research is funded by the European Commission's 7th Framework Programme for research and technological development, Member States and private companies. In particular the Wind EII includes research to improve the economics and the efficiency of power electronics within the development of new large turbines (10–20 MW wind turbines and offshore technology), as solutions for grid integration and resource assessment and spatial planning for the new penetration of wind generation. This implies the development of new PE devices and new control strategies. In grid integration long distance, controllable, HVDC, multi-terminal offshore and onshore solutions will be tested.

The European project TWENTIES will support wind integration with the solutions described in [51], which will require voltage and frequency control methodologies at different levels [52]. E4U project [53] and the European Centre of Power Electronics [54] share the necessity of focusing the research in high efficiency PE devices to avoid big losses.

The increase in IGBT junction temperatures is subject to much research. Whereas the current industry standards is 125 °C, new state-of-the-art series offer up to 150 °C which translates either on a 20% more power for the same size, a corresponding size reduction, or a trade-off between both [48].

Silicon carbide (SiC) is being investigated as a base material for IGBT and other switches because it has the potential to dramatically increase the power density of the power converters [5], and therefore to be a breakthrough. Several research projects in the US are investigating SiC switches (IGBTs, Thyristors) up to 15 kV e.g. within the concept of a transformer-less intelligent power substation (TIPS) [55].

6.1. A vision of the industry

The large majority of power converters used in the industry belongs to the low voltage range. They will have to increase their rated voltage to medium-voltage (MV) levels above 3.3 kV. In the medium term (up to five years) components working at 6.6 kV are possible for the wind power sector because they are already available in the heavy industry sector. However, 3.3 kV converters are still very rare, and in the longer term they should increase to 4.16 kV then 6.6 kV [56]. MV generators are already used in other sectors, and in the wind sector MV generators (10–14 kV) exist without power converters (e.g. DeWind's D8.2 turbine).

Table 4 summarises aspects of the future evolution of wind turbines which would affect power converters and wind turbine configurations, including significant changes. One of the questions, for example, is why each turbine in a wind farm has to have its own power converter and transformer.[9] There could be high economies of scale by transferring some of the functions currently carried out in the WT towards some kind of enlarged substation. Wind farms thus would be designed as a single system rather than as the sum of their wind turbines, and this would affect power electronics. For this vision to realise, MV semiconductor technologies should be developed to the advanced level of their LV counterparts, and aim for higher simplicity [48].

The power converter might be split: the generator-side converter maintained in the wind turbine while the grid-side converter is transferred to the enlarged substation, thus making of the internal wind farm grid a DC grid [48]. Furthermore, the arrival of DC generators, which offer higher power density and efficiency, and a lower cooling demand, would involve that an AC/DC/AC power converter is not needed but only an inverter (see Section 2). Another vision is that wind turbines will be free to generate electricity at any frequency and the whole converter is transferred to a substation with grid adaptation functions.

The topology of converters has an influence in their efficiency and some industry insiders signal a trend towards the widespread use of 3-level converters. The resulting 40% reduction in losses (regarding the 2-level converter) would result in a corresponding reduction in cooling needs [48].

[9] Note that Vestas is already selling this approach with its V82-1.65.

7. Conclusion

During the last ten years power electronics have played a key role in the evolution of wind turbines towards more efficient wind energy capture, better quality of voltage output, better grid integration. The evidence of market research proves the increasing uptake of PE and in particular of the "flagship" manifestation of PE, i.e. power converters.

Wind turbine configurations that include power converters have captured a market share of 85% in 2009, up from 44% in 2000. Turbine manufacturers are introducing an increasing number of WT with full power converters (type D configuration), whereas no significant introduction of a new model of type A configuration occurred in Western countries in the last four years.

Given the global trend towards increasing grid code requirements, the demands to increasing reliability and reduced maintenance costs, power electronics and in particular power converters will eventually be part of all large wind turbines, and within a few years new installation of WT configuration types A and B will be something of the past.

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